

Kondo Physics in a Single Electron Transistor

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(February 7, 2008)

Abstract

How localized electrons interact with delocalized electrons is a question central to many of the problems at the forefront of solid state physics. The simplest example is called the Kondo phenomenon, and occurs when an impurity atom with an unpaired electron is placed in a metal, and the energy of the unpaired electron is far below the Fermi energy. At low temperatures a spin singlet state is formed between the unpaired localized electron and delocalized electrons at the Fermi energy.

The confined droplet of electrons interacting with the leads of a single electron transistor (SET) is closely analogous to an impurity atom interacting with the delocalized electrons in a metal. [1] We report here measurements on a new generation of SETs that display all the aspects of the Kondo problem: the spin singlet forms and causes an enhancement of the zero-bias conductance when the number of electrons on the artificial atom is odd but not when it is even. The singlet is altered by applying a voltage or magnetic field or by increasing the temperature, all in ways that agree with predictions. [2]

When the channel of a transistor is made very small and is isolated from its leads by tunnel barriers it behaves in an unusual way. A transistor can be thought of as an electronic switch that is on when it conducts current and off when it does not. Whereas a conventional field-effect transistor, such as one in a computer memory, turns on only once when electrons are added to it, the small transistor turns on and off again every time a single electron is added to it. [3,4] This increased functionality may eventually make these single electron transistors (SETs) technologically important.

The unusual behavior of SETs is a manifestation of the quantization of charge and energy caused by the confinement of the droplet of electrons in the small channel. Since similar quantization occurs when electrons are confined in an atom, the small droplet of electrons is often called an artificial atom. [5,6] Indeed, the confined droplet of electrons interacting with the leads of an SET is closely analogous to an impurity atom interacting with the delocalized electrons in a metal. [1]

Several theoretical papers have predicted that a Kondo singlet could form in an SET, which would make it possible to study aspects of the Kondo phenomenon inaccessible in conventional systems: With an SET the number of electrons on the artificial atom can be changed from odd to even; the difference in energy between the localized state and the Fermi energy can be tuned; the coupling to the leads can be adjusted; voltage differences can be applied revealing non-equilibrium Kondo phenomena [2]; and a single localized state can be studied rather than a statistical distribution of many impurity states. However, for SETs fabricated previously, the binding energy of the spin singlet has been too small to observe Kondo phenomena. Ralph and Buhrman [7] have observed the Kondo singlet at a single accidental impurity in a metal point contact, but with only two electrodes and without control over the structure, they have not been able to observe all the features predicted. We report here measurements on a new generation of SETs that exhibit all the aspects of the Kondo problem. To make this report accessible to as wide an audience as possible, we discuss here only the qualitative aspects and leave quantitative comparisons for a later publication.

We have fabricated SETs using multiple metallic gates (electrodes) deposited on a GaAs/AlGaAs heterostructure containing a 2-dimensional electron gas (see Figure 1a). First, the electrons are trapped in a plane by differences in the electronic properties of the heterostructure's layers. Second, they are excluded from regions of the plane beneath the gates when negative voltages are applied to those gates. This creates a droplet of electrons separated from the leads by tunnel junctions. This basic technique has been used previously. [8,9,10,11,12] To make our SETs smaller than earlier ones, we have fabricated shallower 2DEG heterostructures [13] as well as finer metallic gate patterns by electron-beam lithography. The smaller size of the SETs is critical to our observation of the Kondo effect. (Dimensions are given in Figure 1a)

Several important energy scales and their relative sizes determine the behavior of an SET (see Figure 1b). At low temperature, the number of electrons N on the droplet is a fixed integer (roughly 50 for our samples). This number may be changed by raising the voltage of a nearby gate electrode which lowers the energy of electrons on the droplet relative to the Fermi level in the leads. The change in energy necessary to add an electron is called U , and in a simple model is the charging energy $e^2/2C$, where C is the capacitance of the droplet. Since U is determined by the Coulomb repulsion between pairs of electrons in the droplet,

it scales approximately inversely with the droplet's radius.

For small droplets, the quantized energy difference between different spatial electronic states becomes important. We call the typical energy spacing between spatial states $\Delta\epsilon$. Another important energy Γ is the coupling of electronic states on the artificial atom to those on the leads, resulting from tunneling. When Γ is made greater than $\Delta\epsilon$, the electrons spread from the artificial atom into the leads, and quantization of charge and energy is lost, even at $T = 0$.

Finally, the energy that determines whether Kondo physics will be visible is kT_K , which is always smaller than Γ (k is Boltzmann's constant and T_K is called the Kondo temperature). [2] By making smaller SETs we have made $\Delta\epsilon$ relatively large, which permits large Γ and thus T_K comparable to accessible temperatures. In semiconductor SETs, Γ can be tuned by changing the voltage on the gates which define the barriers between artificial atom and leads. We find that with our new SETs we can vary Γ slowly as it approaches $\Delta\epsilon$, and thus optimize T_K .

In our experiment, we make two types of measurements. In the first, we apply a voltage of a few μV between the two leads of the SET, called the source and drain, and measure the current that flows through the droplet as a function of the voltage V_g on one of the SET's gates (the middle electrode on the left in Fig. 1a). For such small applied voltage ($< kT/e$), current varies linearly with voltage, and the zero-bias conductance can be measured. We use a 10 Hz AC excitation, and perform lock-in detection of the current. In the second class of measurements, we add a variable DC offset V_{ds} (up to several mV) to our AC excitation, and again use lock-in detection of current to obtain differential conductance dI/dV_{ds} versus V_{ds} .

Varying V_g on an SET typically results in adding an electron to the droplet each time the voltage is increased by a fixed increment proportional to U . Since current can flow through the SET only when the occupancy of the island is free to fluctuate between N and $N + 1$, conductance versus V_g shows a series of sharp, periodically-spaced peaks. [10,11,12] Figure 2c shows this behavior when Γ is made relatively small. When Γ is large, as in Figs. 2a and 2b, we find that these peaks form pairs, with large inter-pair spacing and small intra-pair spacing. The two peaks within a pair have comparable widths and heights, while between pairs the widths vary significantly. These observations are direct evidence that two electrons of different spin are occupying each spatial state. Between paired peaks, N is odd, while between adjacent pairs it is even. Since two electrons corresponding to the pair of peaks are added to the same spatial state, the intra-pair spacing is determined by U . However, when N is even (between pairs) the next electron must be placed in a different spatial state, so the interpair spacing is determined by $U + \Delta\epsilon$.

When $\Gamma \leq kT$ the peaks in conductance versus gate voltage become narrower and larger with decreasing T , as illustrated in Fig. 2c, saturating at a width and height determined by Γ . This behavior results from the sharpening of the Fermi distribution. [10,14] Fig. 2 illustrates that this pattern is followed for large Γ , as well, on the outside edges of paired peaks at all T . However, inside of pairs the peaks become narrower as T is reduced from 800 mK to 400 mK, but then broaden again at low temperatures, resulting in increased conductance in the intra-pair valley. Thus, not only the peak spacing but also the mechanism of conduction itself is different intra-pair from inter-pair. The enhancement of linear conductance at low temperature for odd but not even N is a manifestation of Kondo physics. If N is odd there

is an unpaired electron with a free spin which can form a singlet with electrons at the Fermi level in the leads. This coupling results in an enhanced density of states at the Fermi level in the leads, and hence an enhanced conductance. [15,16] Raising the temperature destroys the singlet and attenuates the conductance.

Another aspect of Kondo physics is the sensitivity of the excess conductance between the pair of peaks to the difference in Fermi levels in the two leads. The extra electron in the droplet couples to electrons in both leads, giving an enhanced density of states at both Fermi levels. [2,17,18] When the applied voltage is large, separating the Fermi levels in the two leads, the electrons at the Fermi level in the higher energy lead can no longer resonantly tunnel into the enhanced density of states in the lower energy lead, so the extra conductance is suppressed. This can be seen in Figure 3, a plot of differential conductance versus V_{ds} . The enhanced conductance is suppressed by a bias of ~ 0.1 mV in either direction.

Figure 3 illustrates how this nonlinear conductance measurement also offers a complementary way of seeing the suppression of the zero-bias enhancement with temperature. By 600 mK, the Kondo resonance has almost disappeared completely between the peak pair near $V_g = -70$ mV.

A magnetic field also alters the Kondo physics. Applying a magnetic field splits the unpaired localized electron state into a Zeeman doublet separated by the energy $g\mu_B B$. This also splits the enhanced density of states at the Fermi level into two peaks with energies $g\mu_B B$ above and below the Fermi level. [2] When the Fermi level of one lead is raised or lowered by a voltage $g\mu_B B/e$ relative to the other lead, electrons can tunnel into the Kondo-enhanced density of states. In differential conductance at high magnetic field, we thus see peaks at $\pm g\mu_B B/e$ (see Figure 3). The splitting of peaks in differential conductance by *twice* $g\mu_B B$ (compared to the spin splitting of the localized state, $g\mu_B B$) provides a distinctive signature of Kondo physics. Since the peaks are broad and overlapping, the distance between their maxima may underestimate their splitting at lower magnetic fields. At 7.5 T, when the peaks no longer overlap, we find their splitting to be $0.033 \pm .002$ meV/Tesla. In comparison to measurements on bulk GaAs, this is significantly smaller than $2g\mu_B B$ yet larger than $g\mu_B B = 0.025$ meV/Tesla. Electron spin resonance measurements have found that spin splittings in a two-dimensional electron gas are suppressed compared with values for bulk samples, sometimes by as much as 35%. [19] Thus, our measurement is consistent with a splitting of $2g\mu_B B$.

Figure 4 shows the differential conductance at low temperature and zero magnetic field as a function of both V_{ds} and V_g . This range of V_g spans the better-resolved pair of peaks near $V_g = -70$ mV in Figure 2 as well as the valleys on either side of it. The bright diagonal lines result from strong peaks in dI/dV_{ds} (outside the range of V_{ds} shown in Figure 3) marking the values of V_{ds} and V_g where N can change to $N+1$ or $N-1$. The slopes of these lines contain information about the relative capacitances of gates and leads to the droplet of electrons. Together with the intrapair spacing of peaks in zero-bias conductance versus V_g at 800 mK (Fig. 2), these relative capacitances give a value for U of ≈ 0.6 meV. $\Gamma/\Delta\epsilon$ is of order unity, so electron wavefunctions in the droplet extend somewhat into the leads, suppressing U . When Γ is reduced for this same device (as in the inset to Figure 2), U increases to ≈ 2 meV. From the difference between inter- and intra-pair spacing in Fig. 2 we find $\Delta\epsilon \sim U$. To determine Γ , we set V_g so that the spatial state corresponding to the paired peaks is empty. Then the width of the peak in dI/dV_{ds} versus V_{ds} corresponding to tunneling into

the empty state is the bare level width $\Gamma \approx 0.2$ meV. This is unmodified by Kondo-enhanced tunneling, which can only occur when the state is singly occupied in equilibrium. All three quantities U , $\Delta\epsilon$ and Γ are considerably larger than $kT = 0.0078$ meV at base temperature.

A white vertical line at $V_{ds} = 0$ in Figure 4 shows that the zero-bias conductance is enhanced everywhere between the paired peaks but not outside the pair. We find, in fact, that there is a zero-bias *suppression* just outside the pair, especially to the side toward negative gate voltage where our Kondo level is unoccupied. [17]

In conclusion, we have observed for the first time all the aspects of Kondo physics in a single-localized-state system. It is apparent that the characteristics of our SET are affected dramatically by the strong coupling of the electron droplet to the leads. In addition to revealing new physics, this may be important in technologically relevant devices, which are likely to have even larger values of Γ , because Γ limits the ultimate speed of such devices.

We would like to thank G. Bunin for help with fabrication, N. Y. Morgan for help with measurements, and I. Aleiner, R. C. Ashoori, M. H. Devoret, D. Esteve, D. C. Glattli, A. S. Goldhaber, L. Levitov, K. Matveev, N. Zhitenev, and especially N. S. Wingreen and Y. Meir for valuable discussions. This work was supported by the U.S. Joint Services Electronics Program under contract from the Department of the Army Army Research Office. D. G.-G. thanks the students and staff of the Weizmann Institute's Braun Center for Submicron Research for their hospitality during his stay there, and the Hertz Foundation for fellowship support. D. A.-M. thanks the Lucent Technologies Foundation for Fellowship support.

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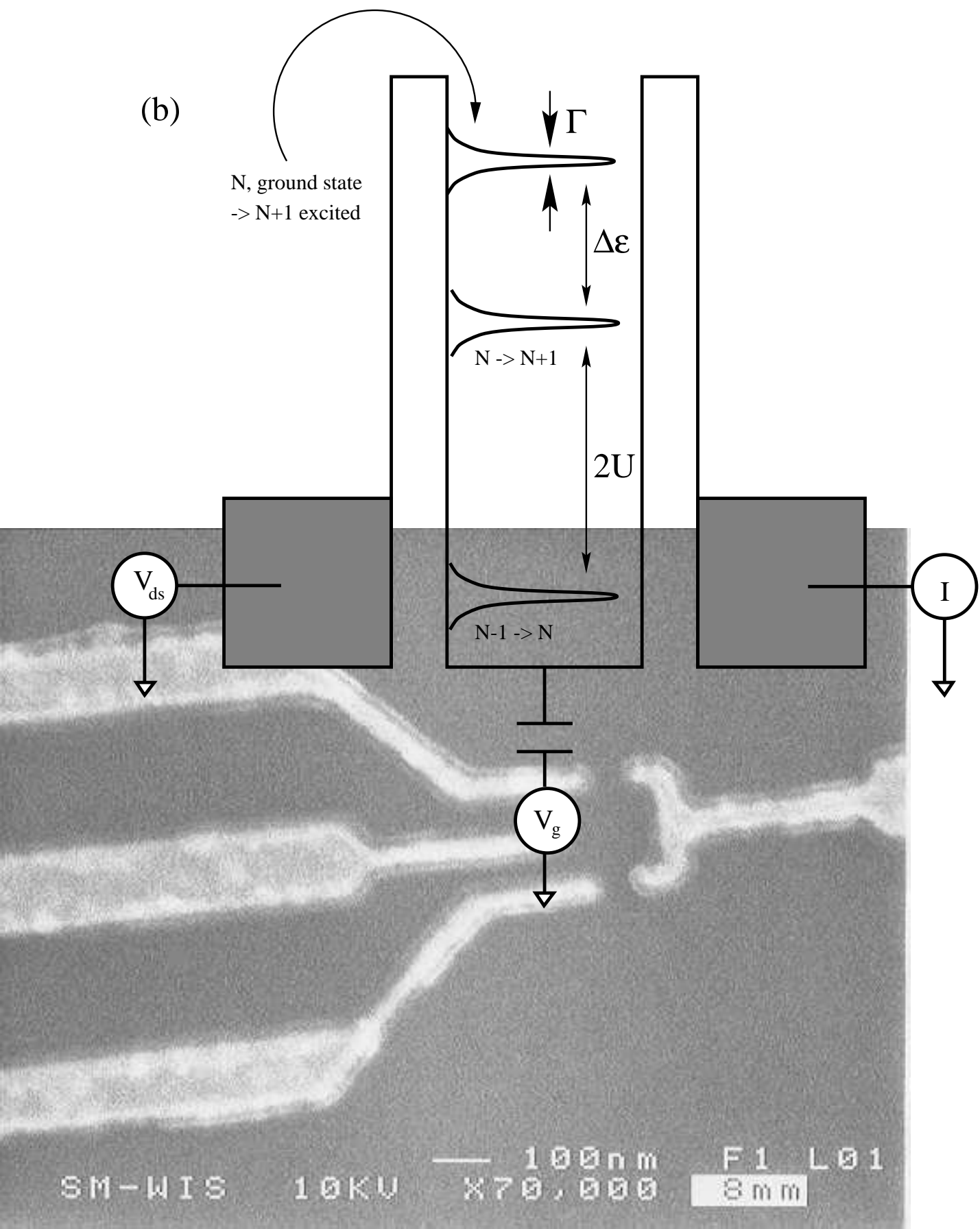
FIGURES

FIG. 1. (a) Scanning electron microscope top view of sample. Three gate electrodes, the one on the right and the upper and lower ones on the left, control the tunnel barriers between reservoirs of two-dimensional electron gas (at top and bottom) and the droplet of electrons. The middle electrode on the left is used as a gate to change the energy of the droplet relative to the two-dimensional electron gas. Source and drain contacts at the top and bottom are not shown. While the lithographic dimensions of the confined region are 150 nm square, we estimate that the electron droplet has dimensions of 100 nm square due to lateral depletion. The gate pattern shown was deposited on top of a shallow heterostructure with the following layer sequence grown on top of a thick undoped GaAs buffer: 4 nm AlAs, $5 \times 10^{12}/\text{cm}^2$ Si δ -doping, 1 nm $\text{Al}_{0.3}\text{Ga}_{0.7}\text{As}$, δ -doping, 1 nm $\text{Al}_{0.3}\text{Ga}_{0.7}\text{As}$, δ -doping, 5 nm $\text{Al}_{0.3}\text{Ga}_{0.7}\text{As}$, 5 nm GaAs cap. [13] Immediately before depositing the metal, we etched off the GaAs cap in the areas where the gates would be deposited, to reduce leakage between the gates and the electron gas. (b) Schematic energy diagram of the artificial atom and its leads. The situation shown corresponds to $V_{ds} < kT/e$, for which the Fermi energies in source and drain are nearly equal, and to a value of V_g near a conductance minimum between a pair of peaks corresponding to the same spatial state. For this case there is an energy cost $\sim U$ to add or remove an electron. To place an extra electron in the lowest excited state costs $\sim U + \Delta\epsilon$.

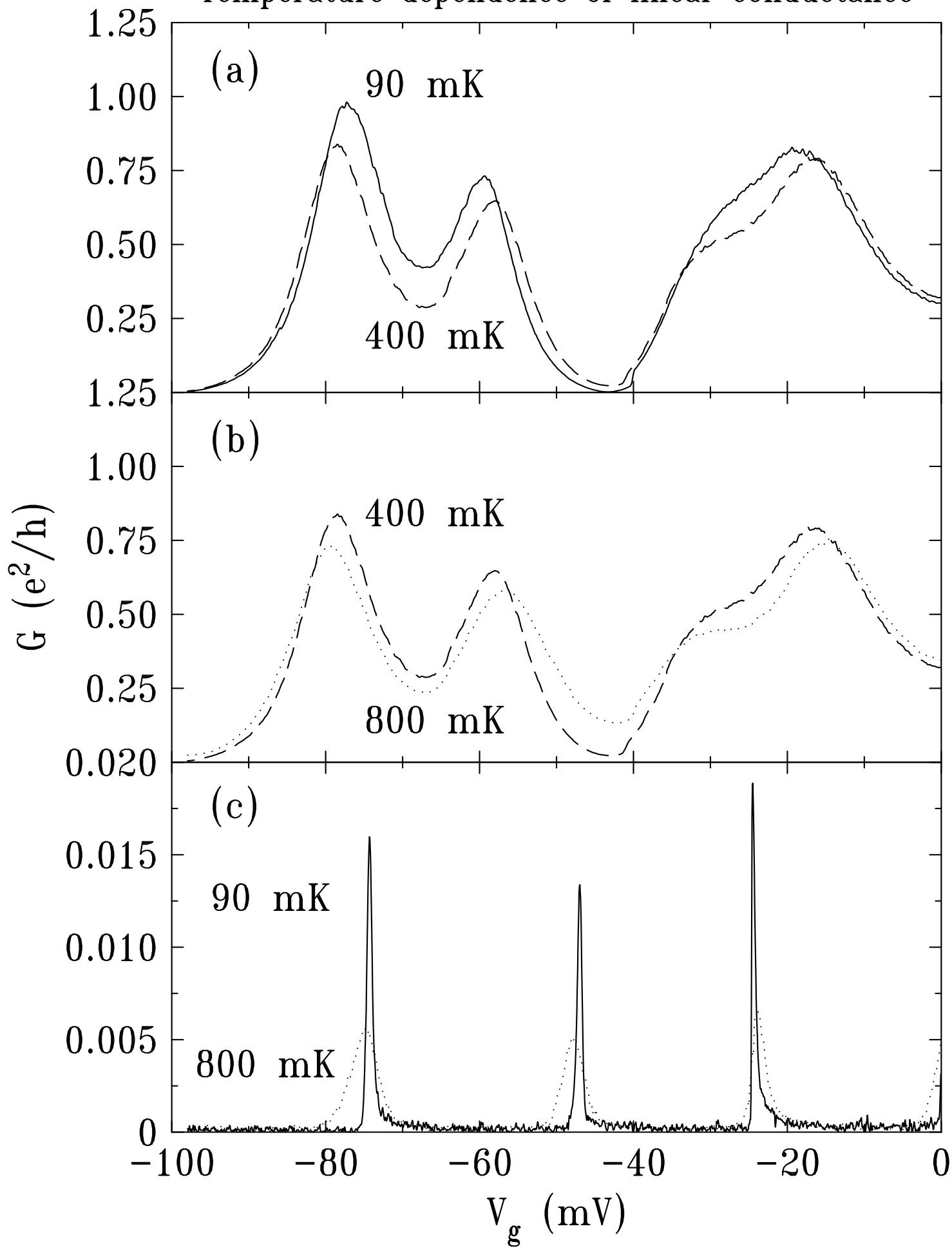
FIG. 2. Temperature dependence of zero-bias conductance through two different spatial states on the droplet. (a) Paired peaks corresponding to the two spin states for each spatial state become better resolved with *increasing* temperature from 90 mK to 400 mK. The intrapair valleys become deeper and the peaks become narrower. (b) From 400 mK to 800 mK the paired peaks near $V_g = -70\text{mV}$ broaden. The peaks near $V_g = -25\text{mV}$ are still becoming better-resolved even at 800 mK since they have larger Γ and hence larger T_K . (c) When Γ is reduced (as illustrated by shorter and narrower peaks), U increases relative to $\Delta\epsilon$, so peak pairing is no longer evident. Since the Kondo phenomenon is suppressed, peaks become narrower as temperature is decreased at all T .

FIG. 3. Temperature and magnetic field dependence of the zero-bias Kondo resonance measured in differential conductance. Temperature suppresses the resonance, while magnetic field causes it to split into a pair of resonances at finite bias. These scans were made with gate voltage halfway between the paired peaks near $V_g = -70\text{mV}$ in Figure 2. Since the energy of the spatial state we are studying changes with magnetic field, the valley between our two peaks occurs at a different gate voltage for each value of magnetic field.

FIG. 4. Differential conductance on a color scale as a function of both V_g and V_{ds} . The white vertical line between the two maxima indicates that there is a zero-bias peak for odd N only.



Temperature dependence of linear conductance



Zero-bias peak in differential conductance

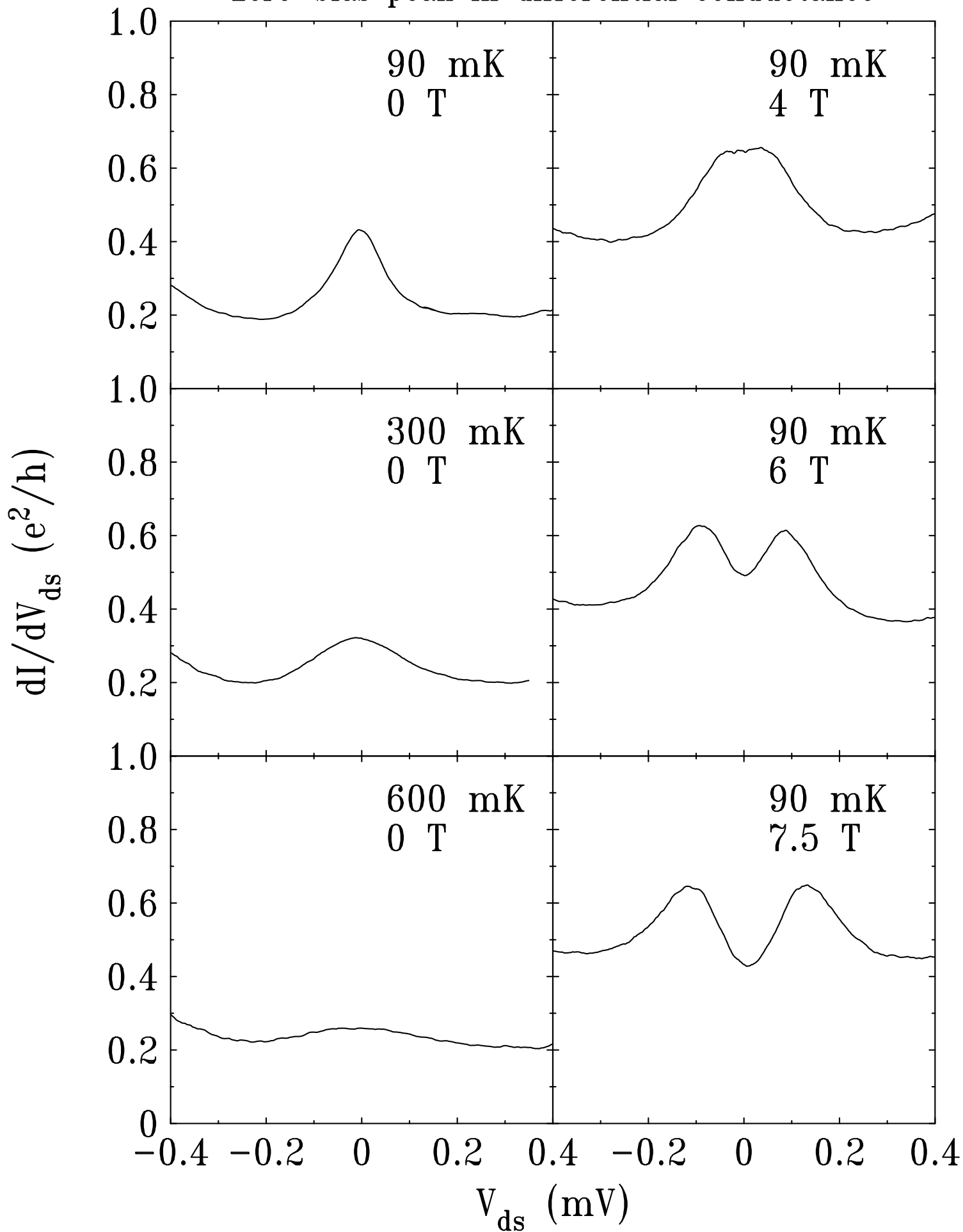


Figure 4

